

The A-X infrared bands of Aluminum Oxide in stars: search and new detections.

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ABSTRACT

We describe a search for the A-X infrared bands of AlO with a view to better understand the characteristics of this radical. These bands are infrequently encountered in astronomical sources but surprisingly were very prominent in the spectra of two well-known, nova-like variables (V838 Mon and V4332 Sgr) thereby motivating us to explore the physical conditions necessary for their excitation. In this study, we present the detection of A-X bands in the spectra of 13 out of 17 stars, selected on the basis of their J-K colors as potential candidates for detection of these bands. The majority of the AlO detections are in AGB stars viz. 9 OH/IR stars, 2 Mira variables and 2 bright infrared sources. Our study shows that the A-X bands are fairly prevalent in sources with low temperature and O-rich environments. Interesting variation in strength of the AlO bands in one of the sources (IRAS 18530+0817) is reported and the cause for this is examined. Possible applications of the present study are discussed in terms of the role of AlO in alumina dust formation, the scope for estimating the radioactive ²⁶Al content in AGB stars from the A-X bands, and providing possible targets for further mm/radio studies of AlO which has recently been discovered at millimeter wavelengths.

Subject headings: Infrared: stars — Stars: AGB and post-AGB — ISM: molecules — Techniques: spectroscopic

1. Introduction

In this study we describe a search to detect the infrared A-X bands of the AlO radical. While several oxide molecules like TiO and VO are routinely encountered in the spectra of cool O-rich stars, AlO is detected rarely and is hence a poorly studied molecule. But, as we proceed to show, AlO could be detected more often if searched for in appropriate sources. The motivation for the study arose from two eruptive variables V838 Mon and V4332 Sgr which have been objects of great interest in recent years. Both objects underwent initial large-amplitude nova-like outbursts but it was soon realized that they were different from classical novae or other known classes of CVs (e.g. Munari et al. 2002). Worth mentioning specifically is the haloed status achieved by V838 Mon by virtue of the striking light echo that adorned it (Bond et al. 2003; Banerjee et al. 2006). A general consensus exists today that they belong to a new class of eruptive variables called intermediate luminosity red transients (ILRTs; Bond et al. (2011)). With the discovery of several more such red transients in recent times (Humphreys et al. 2011), and the likelihood of more discoveries emerging from ongoing synoptic sky surveys, there is currently a great deal of interest in such objects.

Our concern here is with the unusual presence of rarely seen molecular bands of the A-X system of AlO radical, which are strongly seen in the near-infrared spectra of V838 Mon and V4332 Sgr and which could potentially be expected in other ILRTs too. In V838 Mon, these AlO bands were seen in absorption (Evans et al. 2003; Lynch et al. 2004; Banerjee et al. 2005); in V4332 Sgr they were spectacularly seen in emission (Banerjee et al. 2003). Barring V838 Mon, V4332 Sgr and IRAS 18530+0817 (Walker et al. 1997; Evans et al. 2003), a search in the literature shows a severe paucity of A-X band detections of AlO in other sources and a strong need therefore arose to understand why the A-X bands were detected so infrequently. It was perceived that a statistically larger number of detections of the band would help to understand the characteristics and properties of AlO better.

An AlO detection could also help in exploring its role in the formation of alumina dust. Alumina is considered to be the earliest dust condensate in O-rich stars - condensing out at 1760K. In the chaotic silicate hypothesis, the AlO radical plays a pivotal role in silicate and alumina dust formation (Nuth & Hecht, 1990). Observationally too, it was intriguing to see strong AlO emission in V4332 Sgr being simultaneously accompanied by a strong 11 μ m alumina feature (Banerjee et al. 2007). But the interconnection between a gas phase component (AlO) and a solid state component (alumina) needs further study and a statistically large sample of AlO detections should be helpful. From the observational point of view, it is timely to plan or carry out such observations with the present availability of IR

space-borne facilities like SOFIA (Stratospheric Observatory for Infrared Astronomy)¹ and of the James Webb Space Telescope² in the near future. While the mid-IR dust features could be studied by the space-borne facilities, the near-IR AlO bands could be simultaneously studied from the ground. The present study could also help explore an important issue viz. the radioactive ²⁶Al content in AGB stars as discussed in section 3. Finally, it should also be noted that the first millimeter detection of AlO has been recently made in the O-rich supergiant star VY CMa (Tenenbaum & Ziurys 2009) which could lead to similar searches in other objects. The sources detected here could hence be potential targets for such further mm/radio detections; the different transitions occurring in the mm/radio regimes are given in Launila & Banerjee (2009).

It may be noted that a search for near-IR AlO bands had been made earlier too. Luck & Lambert (1974) had looked for the (1,0) bands in selected supergiants and Mira variables but failed to detect them due to miscalculated wavelength positions of the bands (the molecular constants were poorly known then). The wavelengths of the different A-X bands are now well determined from the detailed study of the AlO radical by Launila & Jonsson (1994).

The principal result reported here is the near-IR detection of several bands of AlO in the 1.0–1.35 micron region. These detections are made in 13 out of 17 pre-selected sources thereby giving a high detection rate of almost 75 percent. Our study shows that the A-X bands are thus not so rare and that they should be fairly prevalent in low temperature, O-rich environments.

2. Observations & Analysis

The strategy for source selection was based on the excitation conditions for the A-X bands which arise from transitions between different vibrational levels of the excited A and the ground X electronic states. The vibrational states are low-lying, typically 0.6 to 1 eV above ground level (Launila & Jonsson 1994) and are thus expected to be favorably excited at low temperatures. This is consistent with their appearance in V838 Mon and V4332 Sgr, both of which have cool dusty envelopes with $T < 1000\text{K}$ (Lynch et al. 2004; Banerjee et al. 2003). AlO emission may therefore be expected from similar stellar environments viz. the dusty circumstellar envelopes of evolved stars. A criterion that the $(J - K)$ color should be

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large was hence applied to ensure selection of such sources. We set $J - K > 4$ and chose bright sources to optimize telescope time requirement by setting $J < 10$. A search of the 2MASS point source catalog with these constraints yielded 487 sources. The sample was reduced by ensuring the sources showed the 10 and 18 μm silicate features in their IRAS spectra (Olnon et al. 1986) indicating the O-rich environment necessary for AlO. A further constraint was that the 10 μm silicate feature be broad or display a clearly discernible 11 μm alumina feature on its red wing. Such profiles, it has been argued (Speck et al. 2000; Banerjee et al. 2007), suggest the presence of alumina and hence strengthen the possibility of AlO being present. A final reduction to 17 sources was made considering source accessibility (RA and δ constraints; δ was set > -40 degrees) from the 3.8m UK Infrared Telescope (UKIRT) where the observations were planned and made.

Observations were performed with the UKIRT 1-5 micron Imager Spectrometer (UIST), using an IJ grism and a 4-pix (0.48'')-wide slit; the spectra obtained cover a wavelength range of 0.86 μm – 1.4 μm with a spectral resolution of ~ 320 . Observations of a flat, arc and an early type (B9V-A2V) ratioing star were obtained with the same instrument setting as for the program objects before each set of observations. Before rationing the spectrum of the source with the spectrum of the telluric standard, the hydrogen Pa β and Pa γ absorption features in the spectrum of the latter were removed. The initial processing of the data were carried out using the UKIRT pipeline ORACDR; the extraction and calibration of the spectra were carried out using STARLINK-FIGARO and IRAF. The log of the observations with some source details is given in Table 1.

3. Results

Before presenting the spectra proper, a brief description of the sources is given below to show the nature of the selected sources. The sources are in general heavily obscured with very faint or no optical counterpart in the Digital Sky Survey plates. Most of them show maser emission in one or more of the relevant masing lines of SiO, OH or H₂O. The lines in which such detections have been made and the classification details of the source are summarized in Table 2 along with a few more details.

Figure 1 shows the spectra of 13 stars where AlO is clearly detected while Figure 2 shows the 4 non-detections. Of the 13 stars with detections, 2 are Mira variables, 9 are OH/IR stars and 2 are classified as infrared sources in SIMBAD. Of the 4 non-detections two are infrared sources, one is an OH/IR star and one is possibly a Mira variable. At the top of the Figure 1, an inverted synthetic emission spectrum of AlO is shown whose primary purpose is to show the expected positions of the AlO bands. The wavelengths of the major

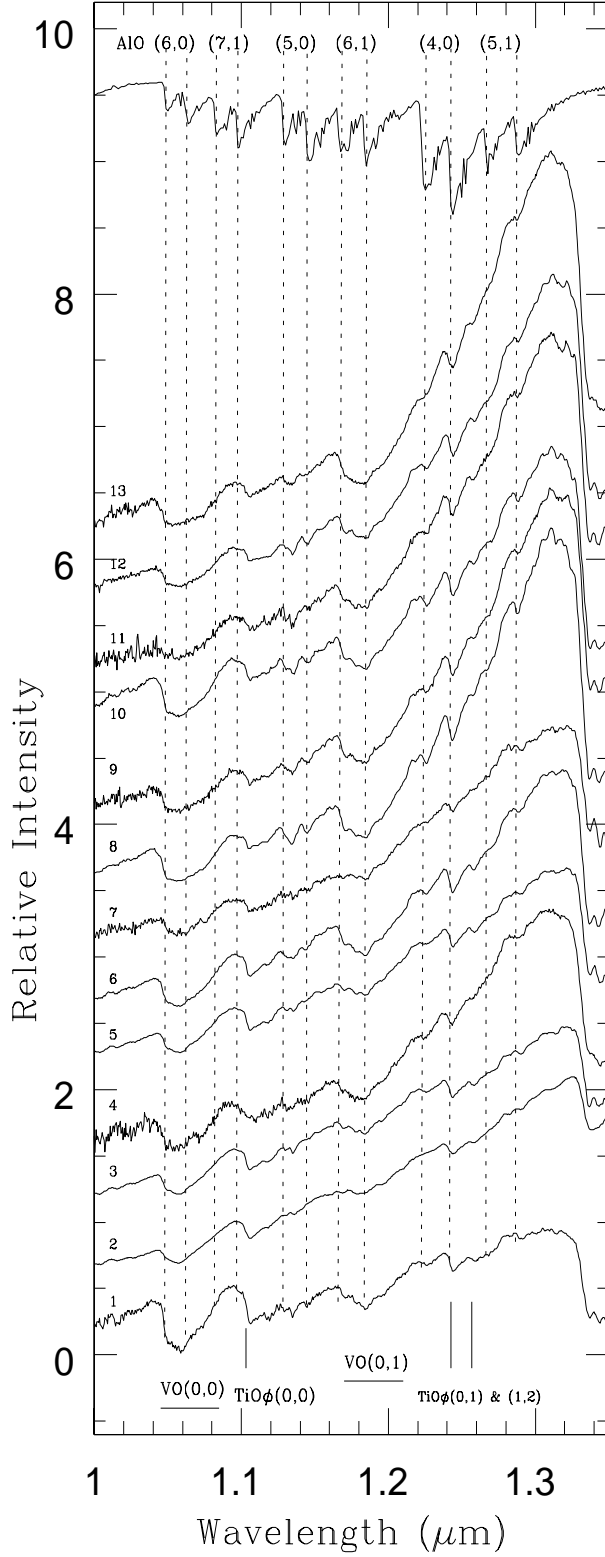


Fig. 1.— Spectra in the 1–1.35 μm region of 13 stars which show AlO features. A synthetic spectrum of AlO is displayed at top with drop lines and labels showing the origin of the different A-X bands. The position of the relevant features of VO and TiO are shown at the bottom. The label numbers of the spectra and the associated source IRAS designations are: 1 - 19178-2620; 2 - 20217+3330; 3 - 18373-0021; 4 - 20267+2105; 5 - 18476+0555; 6 - 18481-0346; 7 - 19043+1009; 8 - 05073+5248; 9 - 18027-2314; 10 - 18069+0911; 11 - 18091-1656; 12 - 18120-1417; 13 - 20077-0625.

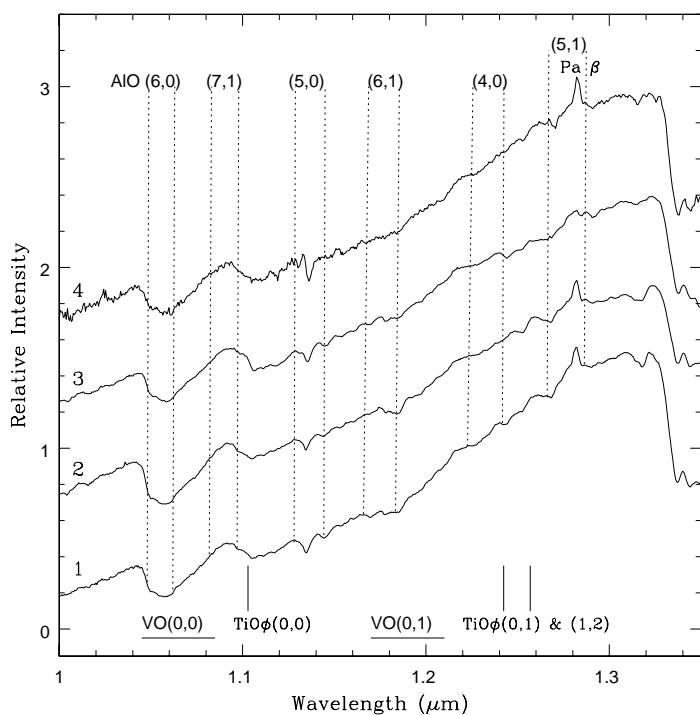


Fig. 2.— Spectra of IRAS 17194-3354, 17209-3126, 18139-1811 and 18530+0817 (labelled 1, 2, 3 and 4 respectively) where AIO features were not detected clearly. As in Figure 1, the expected positions of the relevant molecular features are shown.

Table 1: Journal of observations

IRAS desi- gnation ¹	Obs. Date	Exp. (s)	2MASS (<i>J, H, K</i>)	Airmass Source Std.
05073+5248 ^g	11-08-2008	480	8.204, 5.775, 3.861	1.496 1.543
17194-3354 ^d	29-07-2008	480	9.955, 7.332, 5.671	1.730 1.381
17209-3126 ^d	29-07-2008	480	9.847, 7.287, 5.532	1.659 1.381
18027-2314 ^d	29-07-2008	720	9.474, 6.825, 5.158	1.585 1.381
18069+0911 ^a	25-06-2008	120	9.449, 6.900, 5.137	1.039 1.084
18091-1656 ^e	28-06-2008	400	9.204, 6.613, 5.057	1.296 1.090
18120-1417 ^d	29-07-2008	540	8.552, 6.004, 4.523	1.477 1.381
18139-1811 ^d	29-07-2008	480	9.673, 7.067, 5.372	1.634 1.381
18373-0021 ^e	28-06-2008	160	9.446, 6.498, 4.595	1.112 1.031
18476+0555 ^e	28-06-2008	480	9.424, 6.958, 5.245	1.047 1.031
18481-0346 ^e	28-06-2008	600	9.775, 7.271, 5.571	1.132 1.031
18530+0817 ^a	25-06-2008	160	9.404, 6.905, 5.119	1.143 1.084
19043+1009 ^c	25-06-2008	160	9.355, 6.990, 5.259	1.071 1.092
19178-2620 ^b	25-06-2008	160	9.643, 6.720, 4.588	1.639 1.200
20077-0625 ^f	28-06-2008	120	6.906, 3.923, 2.059	1.124 1.008
20217+3330 ^f	28-06-2008	540	8.768, 6.239, 4.674	1.031 1.008
20267+2105 ^f	28-06-2008	540	8.792, 6.310, 4.340	1.001 1.008

¹Telluric standards used: a - BS 6977 (A0Vn), b - BS 7400 (A0V), c - BS 7390 (A0V), d - BS 6581 (A2V), e - BS 6992 (B9V), f - BS 7891 (A0V), g - BS 1692 (A0V). Mean airmass of the source and standard are given in the last 2 columns.

Table 2. Source descriptions¹

IRAS designation	SiO			OH		H ₂ O maser	Source details
	v=1, J=1-0 43.12 GHz	v=2, J=1-0 42.82 GHz	v=1, J=2-1 86.24 GHz	1612 MHz	1667 MHz	22.2 GHz	
05073+5248	✓(1)	✓(1)		✓(2)	✓(3)	✓(1)	Mira, Sp. class M10, $P = 635$ d (4)
17194-3354							IR source, poorly studied (5)
17209-3126				×(2)			IR source, poorly studied (5)
18027-2314	✓(6)	✓(6)		✓(2)			OH/IR star (2) ²
18069+0911	✓(1)	✓(1)				✓(1)	Mira, P unknown (1,4)
18091-1656	✓(6)	✓(6)		✓(17)			OH/IR star (17) ³
18120-1417	×(8)	×(8)		✓(17)	✓(3)		OH/IR star (3,17)
18139-1811				✓(2)	×(3)		OH/IR star (2,5)
18373-0021							IR source, poorly studied (5)
18476+0555				✓(7)			OH/IR star (7)
18481-0346	✓(8)	✓(8)					IR source (5)
18530+0817				×(9)			Mira? (10) ⁴
19043+1009				✓(17)		✓(11)	OH/IR star (17)
19178-2620	✓(13)	✓(13)	✓(13)	✓(17)	✓(3)	×(12)	OH/IR star (3,17)
20077-0625	✓(14)	✓(14)	✓(14,15)	✓(2)			OH/IR star (2) ⁵
20217+3330				×(9)			IR source (5)
20267+2105			✓(18)		✓(3)		OH/IR star (3)

¹A check mark indicates a detection and a cross an attempted search followed by a non-detection. The numbers in parentheses are the relevant references which are (1) Kim et al. (2010) (2) te Lintel Hekkert et al. (1991) (3) Le Squeren et al. (1992) (4) Benson et al. (1990) (5) SIMBAD database (6) Deguchi et al. (2000) (7) Eder, Lewis & Terzian (1988) (8) Deguchi et al. (2004) (9) Lewis, Eder & Terzian (1990) (10) Walker et al. (1997) (11) Cesaroni et al. (1988) (12) Deguchi et al. (1989) (13) Nyman, Hall & Olofsson (1998) (14) Spencer et al. (1981) (15) Le Bertre & Nyman (1990) (16) Hansen & Blanco (1975) (17) te Lintel Hekkert et al. (1989) (18) Cernicharo et al. (1997)

²The JHK magnitudes are found to be variable as expected for OH/IR stars, between 2MASS values and $J = 13.784$, $H = 8.444$, $K = 6.241$ as reported by Deguchi et al. (2002).

³The JHK magnitudes are found to vary between 2MASS values and $H = 6.654$, $K = 5.631$ as reported by Deguchi et al. (2002).

⁴A detailed infrared study has been done by Walker et al. (1997) who suggest it could be Mira variable; discussed further in the text.

⁵Le Bertre & Nyman (1990) give a period of ~ 650 days, SIMBAD lists it as a Mira with $V = 20$ from the study of Hansen & Blanco (1975).

Table 3: A²Π_{*i*} - X²Σ⁺ bandheads of AlO in the 1 to 1.35 μm region

Band	Wavelength (μm)	A ² Π _{3/2}	Wavelength (μm)	A ² Π _{1/2}
(3,0)		1.3589		1.3358
(4,0)		1.2417		1.2226
(5,0)		1.1443		1.1281
(5,1)		1.2863		1.2661
(6,0)		1.0619		1.0480
(6,1)		1.1834		1.1659
(7,1)		1.0969		1.0818

bandheads of the A-X system in the 1–1.35 micron region are listed in Table 3. Drop lines at the position of the band origins are also shown. The clearest detections of AlO are in the (4,0) bands at 1.2417 and 1.2226 μm . The 1.2863 μm component of the (5,1) band is also clearly seen while a small but discernible dip is also seen at the position of the counterpart 1.2661 μm feature. Also there are discernible bandheads at the predicted positions of the (5,0) bands at 1.1443 and 1.1281 μm indicating that these bands are also present. We have compared our spectra with those of Joyce et al. (1998) and Hinkle et al. (1989) wherein a comprehensive identification of the *J* band molecular features in cool stars is given. For the TiO bands we have also referred to Jorgensen (1994) and Galehouse, Davis & Brault (1980). From these studies, it is confirmed that no other molecular features are expected to be present at the positions of the (4,0), (5,0) and (5,1) bands detected here, and discussed above, thereby strongly suggesting they are due to AlO. The only case of overlapping of features is between the 1.2424 μm component of the TiO ϕ (0,1) system and the 1.2417 μm AlO feature. Using the molecular constants from Jorgensen (1994; see figure 5), the ϕ system is expected to produce the (0,1) and (1,2) band heads at 1.2424 and 1.2568 μm respectively. In the spectra, the 1.2568 μm TiO bandhead is weak but is still consistently seen in the spectra (its position is marked in Figure 1). The only other TiO feature that is seen is the ϕ (0,0) system with its bandhead at 1.1035 μm .

The deep absorption at the red end of the *J* band due to water in the source makes it difficult to comment on the possible presence of the (3,0) bands at 1.3589 and 1.3358 μm . The 1.3358 μm band was seen in V4332 Sgr where water absorption was weak (Banerjee et al. 2003). VO has two prominent A-X bands in this region namely VO (0,0) with its bandhead at 1.056 μm and VO(1,1) extending between 1.1682 μm to 1.2158 μm (Cheung et al. 1982). Both these bands are seen in the spectra of several stars (Joyce et al. 1998; Hinkle et al. 1989). We suspect that the VO(0,1) band is present but strongly contaminated with the AlO (6,1) bands. The reason for this is that VO (0,1) is known not to have any conspicuous bandhead as pointed out by Hinkle et al. (1989, see Table 2 therein) who therefore while assigning a wavelength to this band give a central frequency rather than a bandhead frequency. The spectra of R Cas in Joyce et al. (1998, Figure 3 therein) also supports this where it is seen that while VO (0,0) has a sharp bandhead, VO (0,1) on the other hand displays a broad feature without a significant bandhead. However in our spectra a prominent bandhead is seen at the onset of the VO (0,1) band which we feel is instead due to the 1.1659 μm band of AlO (6,1). In addition, there is also a clear indentation in the VO (0,1) feature at ~ 1.184 μm that coincides with the 1.1834 AlO (6,1) component. We hence infer that although VO (0,1) may be present, the (6,1) bands of AlO are also present in the 1.16 to 1.21 μm region.

In many of the spectra in Figures 1 and 2, especially those in the latter, an absorption feature at 1.1345 μm appears to be seen which does not correspond with any of the expected

molecular features. This is likely to be an artifact arising from a strong H₂O telluric absorption feature expected at this position. This feature appears to have been incompletely removed in the ratioing process due to the slight airmass differences between the source and standard star during observations (as indicated in Table 1).

An intriguing result is the variation seen in the spectrum of the source IRAS 18530+0817. This is the only source from our list which has been studied in detail in the near and mid-infrared earlier (Walker et al. 1997). A comparison between our *J* band spectrum and a similar one taken on 19 May 1995 by Walker et al. (1997, Figure 2a therein) shows considerable changes. AlO absorption bands are prominently seen in the 1995 spectrum but have disappeared in our spectrum (the source is included in the non-detections in Figure 2). The H Paschen β line at 1.2818 μ m is also seen in emission in our data. Interestingly the 10 μ m silicate profile, which shows a clear alumina component at 11 μ m, is also found to vary. Most striking is the change in the 10 μ m profile in the two IRAS spectra, taken in 1983 and separated by 6 months, wherein a large decrease in intensity level as well as striking changes in the profile morphology are seen. The bright emission feature at 9.5 μ m (due to silicates) remains relatively unaltered whereas the emission component around 11 μ m (presumably due to alumina) has almost disappeared. Since AlO is also established to be varying in the source, it will be interesting to take simultaneous *IJ* spectra of the AlO bands as well as that of the 11 μ m alumina feature and see what kind of a correlation is found. From an astrochemistry point of view, this may be a meaningful study as discussed in section 1.

4. Discussion

The variation of the AlO band strengths in IRAS 18530+0817 may be a sign of a more generic trait in variability. It may be related to the anomalous variation of the optical B-X bands of AlO, notably the (0,0) 4842 Å band, in Mira variables reported by Keenan, Deutsch & Garrison (1969). Keenan, Deutsch & Garrison (1969) conclude that the strength of the AlO bands can be quite different in two Mira variables of the same temperature and the same star observed at two different maxima can have extremely different AlO strengths (hence the anomalous behavior). This variation in strengths from cycle to cycle is not shared by other molecules like ScO and VO which vary predictably with spectral type. The bands are occasionally found to go into emission from absorption and we speculate that this must be similarly happening to IRAS 18530+0817, and possibly the other stars with non-detections in Figure 2, wherein the AlO absorption features may have been filled in by emission (the Paschen β line going into emission could be an indication of this). The

anomalous behavior of the B-X bands is still an unexplained phenomenon.

An AlO detection could open the door for a subsequent search for radioactive ^{26}Al in the object. The same A-X band of AlO, with the Al atom therein being either ^{26}Al or ^{27}Al , can be sufficiently separated in wavelength to be resolved at intermediate/high spectral resolution (Banerjee et al. 2004). For example, our calculations show that the origin of the (4,0) bands of $^{27}\text{Al}^{16}\text{O}$ and $^{26}\text{Al}^{16}\text{O}$ occur at 1.22558 and 1.22053 μm respectively and hence resolving even individual rotational lines should be possible at higher resolution. The yield of $^{26}\text{Al}/^{27}\text{Al}$ in AGB stars has been the subject of considerable study (e.g reviews by Prantzos & Diehl (1996), Lugaro & Karakas (2008)). It may be noted that the bulk of our positive AlO detections are in OH/IR stars and Mira variables which are essentially AGB stars. The OH/IR stars in particular are very evolved stars belonging to the tip of the AGB branch enroute to their becoming planetary nebulae. Low mass AGB stars (≤ 3 to $4 M_{\odot}$) produce relatively smaller amounts of ^{26}Al primarily from hydrogen shell burning (Lugaro & Karakas 2008) while ^{26}Al production is enhanced in high mass and super AGB stars (Siess & Arnould 2008) due to the process of hot bottom burning and the third dredge up process. The theoretical $^{26}\text{Al}/^{27}\text{Al}$ yield can be compared directly with observed yields in stardust grains in meteoritic samples. For O-rich atmospheres considered in this study, oxide grains need to be considered and from Nollett, Busso & Wasserburg (2003) the expected yield of $^{26}\text{Al}/^{27}\text{Al}$ in a typical low-mass $1.5M_{\odot}$ AGB star is seen to lie between 10^{-3} to 10^{-1} . The highest values are reached after the star has undergone several thermal pulses - a situation relevant for the evolved OH/IR stars. In high mass AGB stars, the $^{26}\text{Al}/^{27}\text{Al}$ yield may be even higher (Prantzos & Diehl 1996). At the low yield values of 10^{-3} , detecting the the ^{26}AlO component against the ^{27}AlO emission background will be challenging spectroscopically. However, at the higher yields the chance of a detection should be good. In any case, even being able to observationally set a well-constrained upper limit on the $^{26}\text{Al}/^{27}\text{Al}$ ratio should be useful (especially since the rate for the key reaction $^{26}\text{Al}(p,\gamma)^{27}\text{Si}$ that destroys ^{26}Al is largely uncertain; van Raai et al. (2008)). A robust ^{26}Al detection should also help in tightly constraining the contribution of AGB stars to the galactic ^{26}Al emission manifested through the 1.8 MeV γ ray line.

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